Studying Piton de la Fournaise Volcano based on Correlations of Ambient Seismic Noise

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1. Introduction of La Reunion and Piton de la Fournaise
2. Studies based on seismic noise
La Réunion Island and Piton de la Fournaise Volcano

- Piton des Neiges (3069 m, last eruption 12 ka)
- Laboratory of GeoSciences at La Reunion University (LGSR)
- Piton de la Fournaise (2632 m, presently active)
- Piton de la Fournaise Volcano Observatory (OVPF)

La Réunion:
French Overseas Department
2512 km²
840000 hab.
Origin of the La Réunion Volcanism

La Réunion Island is the latest manifestation of the mantle plume that generated the Deccan Traps.

Comparing with the Hawaii plume:

• significantly weaker magma production rate
• significantly slower plate motion (~1cm/year)
• slightly younger oceanic lithosphere
History of the La Réunion Volcanism

La Réunion Island is the subaerial part of a 7 km high oceanic shield volcano with a diameter of 220–240 km started around 5-8 Ma ago.

- The initial evolution was characterized by two adjacent volcanoes: Alizés and Piton des Neiges.
- Around 530 ka ago, the Alizés volcano stopped and Piton de la Fournaise appeared.
- Between 530 ka and 12 ka Piton des Neiges and Piton de la Fournaise showed contemporaneous activity.
- Since 12 ka, eruptions are restricted to Piton de la Fournaise.
- Migration of the volcanic activity in time is not simply related to the plate motion.

from Michon et al. (2007)
More information in the porter by Thomas Staudacher
TU20 “60 years of volcanic eruptions at Piton de la Fournaise volcano”
and in the talk by Andrea Di Muro
“The plumbing system of Piton de la Fournaise volcano (Réunion Island): a geochemical perspective”
Piton de la Fournaise Volcano Observatory (OVPF)

- Created in 1979
- Funded by IPGP, CNRS, and La Réunion authorities
- Current team of 4 scientists and 7 technical and administrative staff
- Operates geophysical and geochemical monitoring networks
- Digital continuous seismic records are available since 1999
- Major upgrade of the seismic and GPS networks in 2009 with the UNDERVOLC project

Presentation by the OVPF members at the Chapman conference:
  Philippe Kowalsky, M14 poster
  Andrea Di Muro, talk this afternoon
  Thomas Staudacher, TU20 and TU21 posters
Before 2009

- Seismic network was mostly composed of short-period one-component instruments with analogous data transmission
- Deformation measurements were mostly concentrated on the main edifice
- Digital seismic data started in 80-s
- Continuous seismic data started in 1999
Piton de la Fournaise new Seismic and GPS networks

Since 2009: 20, 3C broad-band seismic stations with continuous recording + 18 GPS. Continuous waveforms are available.

More information in the poster by Philippe Kowalski
M14 “Evolution of monitoring networks of Piton de la Fournaise volcano over 30 years”
and the poster by Thomas Staudacher
TU21 “Permanent and cinematic GPS network at Piton de la Fournaise”
OVPF data distribution

VOLOBSIS portal:  
http://volobsis.ipgp.fr

IPGP data center:  
http://centredesdonnees.fr

RESIF data portal:  
http://www.resif.fr/portal
Period well-covered by seismic observations

Continuous seismic data

Major event: the 2007 caldera collapse

Modernization of the seismic network
Piton de la Fournaise Seismic activity

Mostly Volcano-Tectonic events with no apparent spatial migration along time, except for the 1998 seismic swarm.

A typical seismic swarm preceding an eruption at PdF.

V. Ferrazzini, pers. Comm.
Piton de la Fournaise Seismic activity

Mostly Volcano-Tectonic events with no apparent spatial migration along time, except for the 1998 seismic swarm.

V. Ferrazzini, pers. Comm.
Piton de la Fournaise magmatic system

Interpretation of geophysical observations

from Prono et al. (2009)

More information in the talk by Andrea Di Muro
“The plumbing system of Piton de la Fournaise volcano (Réunion Island): a geochemical perspective”
Continuous Monitoring of temporal changes of the structure at depth with seismic observations

Basic idea: changes in seismic waveforms or travel times may reflect changes in the properties of the media where the waves propagate.

Approaches

• **repeated seismic tomographies**
  
good spatial resolution but low sensitivity because of changing source-station configurations; works well for detection of strong changes, e.g., related to volcanic eruptions (e.g., Patane et al., 2006; Kulakov et al.); requires sustained and well-distributed seismicity

• **comparison of waveforms from repeated seismic sources**
  
(e.g., Poupinet et al., 1984; Snieder et al., Snieder et al., 2002) natural repeated sources (seismic doublets) are difficult to find; implementation of repeated explosions can be very expensive

• **using noise correlations as repeated seismic sources**
  
(e.g., Sens-Schöfeder and Wegler, 2006; Stehly et al., 2007; Wegler and Sens-Schöfeder, 2007; Brenguier et al. 2008) subject of this presentation
Studying the Earth's interior based on correlations of ambient seismic noise

- Introduction: extraction of deterministic signals (Green functions) from records of ambient seismic noise
- Applications for tomography
- Application for monitoring of active geological objects (volcanoes, seismic faults)
- Results from the Piton de la Fournaise, La Réunion
Modern digital seismograms

> 95% of seismograms are records of “seismic noise”: waves continuously excited by the coupling between the ocean (atmosphere) and the Solid Earth.
First-order approximation: ambient seismic noise is a random seismic wavefield
Extracting Green function from random wavefields

For a random wavefield with sources distributed homogeneously everywhere in the medium it can been shown that:

\[
\frac{d}{d\tau} C_{A,B}(\tau) = \frac{-\sigma^2}{4a} \left( G_a(\tau, \vec{r}_A, \vec{r}_B) - G_a(-\tau, \vec{r}_A, \vec{r}_B) \right)
\]

Computing noise cross-correlations between A and B is equivalent to an event occurred at A and recorded at B.
Extraction of surface waves from noise cross-correlations

cross-correlations from 30 days of continuous vertical component records (2002/01/10-2002/02/08)
Extraction of surface waves from noise cross-correlations

Figure 3. Snapshots of the normalized amplitude of the ambient noise cross-correlation wavefield with TA station R06C (star) in common at the centre. Each of the 15–30 s band-passed cross-correlations is first normalized by the rms of the trailing noise (ibid. 2008) and fit with an envelope function in the time domain. The resulting normalized envelope functions amplitudes are then interpolated spatially. Two instants in time are shown, illustrating noise-out and the unequal azimuthal distribution of amplitude.

Lin et al., 2009
Noise-based surface-wave tomography of California

Step 1: computing noise-cross-correlations
Step 2: measurement of dispersion curves (period-dependent velocities)
Step 3: regionalization of the measured dispersion curves
Step 4: depth inversion

cross-correlations of vertical component continuous records (1996/02/11-1996/03/10)
0.03-0.2 Hz

3 km/s - Rayleigh wave
Step 2: measurement of dispersion curves (period-dependent velocities)

Measurements at longer periods (larger wavelengths) are sensitive to deeper parts of the Earth

Shapiro et al., 2005
Noise-based surface-wave tomography of California

Step 3: regionalization of the measured dispersion curves

7.5 s cross-correlation

Shapiro et al., 2005
Step 3: regionalization of the measured dispersion curves

18 s cross-correlation

Shapiro et al.
Noise-based tomography from the USArray

Ritzwoller et al., 2011
Noise-based tomography of Iceland

distribution of shear-wave velocities in the uppermost mantle

Landes et al., in preparation
Noise-based seismic monitoring

• seismic noise can be recorded **continuously**

• computing cross-correlation of seismic noise between two stations from long enough records is equivalent to an experiment when a source is acting at location of one of stations and recorded at another

• repetitive computations of noise cross-correlations are equivalent to using repetitive seismic sources and can be used to detect changes in the medium
Main results

Velocity variations can be measured with an accuracy of 0.1% with a temporal resolution of a single day.

High-frequency noise correlations are mostly sensitive to superficial layers where velocity variations show a strong seasonal influence of precipitation.
Application of the seismic noise based methods to the Piton de la Fournaise Volcano

Major event: the 2007 caldera collapse

Continuous seismic data

Short-period stations

Broadband stations

Modernization of the seismic network

Cumulated lava volumes (million cubic meters)

years


Before

After
Surface wave tomography of the Piton de la Fournaise Volcano

Brenguier et al., 2007

Seismic network

Rayleigh waves extracted from noise cross-correlations

Brenguier et al., 2007
Surface wave tomography of the Piton de la Fournaise Volcano

Brenguier et al., 2007
Noise based monitoring of the Piton de la Fournaise volcano (Brenguier et al., 2008)

Step 1: computing noise cross-correlations in a moving window for different periods of time

Step 2: measuring travel time differences

How to measure time travel-time differences from relatively low-frequency signals?

Examples of cross-correlations for three dates before the June 2009 eruption
Measuring velocity variations from scattered arrivals

In a case of a homogeneous velocity perturbations in the media travel times of all waves change proportionally to this perturbation.

This results in a **stretching of waveforms**

Measuring the **stretching coefficient** is equivalent to measuring the **relative travel-time or velocity perturbation**
Noise based monitoring of the Piton de la Fournaise volcano
(Brenguier et al., 2008)
Short-term variations during 1999-2000

Averaged in a 7 day moving window

Brenguier et al., 2008
Short-term variations during 1999-2000

Regionalization of velocity perturbations

9 days before eruption of June 2000

4 days before eruption of June 2000

Detected velocity variations are localized in the vicinity of the main crater: consistent with a shallow source of deformation

Brenguier et al., 2008
Eruption of July 2006
Possible interpretation of observed velocity variations

The observed short-term decreases in seismic velocities (shear modulus) may result from the inflation and dilatation of a part of the edifice caused by the overpressure within the volcano plumbing system.
Velocity variations observed during large earthquakes
• are slightly weaker than those observed on the PdF volcano
• are not localized to a small area
Long-term seismic velocity changes from noise cross-correlations

• long-term velocity decrease before 2004: edifice pressurization and/or damaging
• major event in 2007
• velocity increase after 2007

Clarke et al., 2011
Erupted lava volumes

Seismicity

Summit deformation from GPS

Seismic velocity changes
Large velocity variation during the 2007 eruption

Is it related to the caldera collapse?
Results

Large velocity variation during the 2007 eruption averaged in a 30 day moving window

Detailed time history shows that the velocity decrease started a few days before the caldera collapse
Large velocity variation during the 2007 eruption

Detected velocity perturbations are mostly located east from the main cratered where a strong flank destabilization was triggered by the eruption.

30 March 2007, start of the seismic swarm and magma injection

Lateral magma injection

Eruption period

Unreliable measurements due to the crater collapse (5-7 April 2007)

seismic velocity perturbation detected with noise cross-correlations

eastward displacement detected with INSAR interferometry

Velocity variation is likely related to the damaging caused by the flank destabilization
Conclusions

- Seismic noise can be used to measure continuous variations of seismic velocity (shear modulus) within the volcanic edifice.

- Observed relative velocity variations are small (<1%) but significantly larger than the associated deformation.

- Small (~0.1%) velocity decreases associated with eruptions and magmatic intrusions are likely related to the inflation and dilatation the edifice caused by the overpressure within the shallow part of the volcano plumbing system.

- Large (~1%) velocity decrease during the 2007 eruption is likely related to the damaging caused by the flank destabilization.

- Better understanding of the underlying non-linear physical mechanism is required for more quantitative interpretation of observations.
The end
Application of the seismic noise based methods to the Piton de la Fournaise Volcano

Major event: the 2007 caldera collapse

- Continuous seismic data
- Short-period stations
- Broadband stations
- Modernization of the seismic network

Cumulative lava volumes (millions cubic meters)

Years:
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
- 2012

Before and After images of the caldera.
Observations with new broadband stations
**Increase** of seismicity rate between 1999 and 2003

Rivemal et al., in preparation
Summit GPS baseline changes

Inter-eruptive inflation before 2007 and contraction after 2007

Courtesy of Staudacher, OVPF
Long-term seismic velocity changes from noise cross-correlations

Clarke et al., 2011
The 2007 eruption

InSAR shows a widespread flank deformation of max. 1.4 m eastward.

Seismic velocity changes show that this strong deformation is likely to have been triggered by a lateral magma injection.

Could the large flank deformation have favored the lateral magma transport?

Clarke et al., 2011
Ongoing flank deformation

Elastic deformation?

Instability triggered in 2007?

Interferogram (Oct 17, 2009 to Oct 26, 2010; courtesy JL Froger)

Courtesy of Staudacher, OVPF